ROCK CLASSIFICATION ON THREE CO-ORDINATES[1]

ALEXANDER N. WINCHELL

There are many published classifications of igneous rocks, and their very number and variety are an indication of the difficulties inherent in the problem of constructing a satisfactory schematic arrangement—difficulties which are due largely to the fact that rocks are not chemical units, but mechanical mixtures, whose proportions may vary almost indefinitely in a great many ways.

It is generally admitted that at present the most satisfactory classifications are based upon, first, mineral (or chemical) composition, and, second, texture or geologic mode of occurrence. It is to be hoped that with advancing knowledge classifications may be based largely upon the principles of eutectics and the method of genesis of igneous types; at present the use of such conceptions as bases of classification may be recognized as desirable, but must be held in abeyance as impossible without more information.

A classification of igneous rocks based almost wholly upon chemical composition has been worked out in detail by Cross, Iddings, Pirsson, and Washington.[2] It has come into use gradually by an increasing number of petrologists, but its service to science is restricted by two facts: first, it commonly ignores the actual mineral composition in favor of an imaginary mineral composition known as the "norm," and, second, it cannot be used until the chemical composition[3] of the rock is known. Its great advantage lies in the fact that it reveals chemical characteristics and relationships with fidelity and clearness.

The classification of Rosenbusch,[4] which has been developed

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *A Quantitative Classification of Igneous Rocks.* 1903.

[3] A microscopic determination of the quantitative mineral composition may be used as a substitute for a chemical analysis only when the norm and the mode are the same.

[4] *Elemente der Gesteinslehre.* 1910.

and modified by its author concurrently with the development of petrography during the past forty years, has come to have a very wide usage, either in its author's own form, or as modified by geologists in some respects to suit local needs. One of its elements of strength is the fact that it is based upon the mineral composition, and only secondarily defined in terms of chemical composition. It is also based upon the geological conditions of formation, so that the rocks of batholiths are separated from those of surface flows and both are separated from those of dikes and sills. Rosenbusch has never put this classification into diagrammatic form, and this fact has aided him in adapting it to advancing knowledge and enabled him to employ in some groups as minor bases of division factors or properties wholly inapplicable to other groups.

It is surprising that even in the latest form Rosenbusch still recognizes geological age as a basis of classification in some groups. He also emphasizes the important distinction between alkaline and other rocks.

In spite of its relative inflexibility a diagrammatic or tabular scheme of classification has numerous advantages, to which, for example, Kemp's[1] greatly simplified modification of the Rosenbusch classification owes much of its popularity. Such tabular schemes have heretofore been arranged on two co-ordinates. The relationships of rocks are so numerous and complicated that one of the chief defects of diagrammatic devices has been that they brought out so few of these affinities. By the use of transparent paper such a classification may be constructed on three co-ordinates as shown on the triple insert, and the advantages of such a scheme obtained without the defect mentioned. A classification on three co-ordinates does not show all the relationships that exist, but it exhibits many more than the ordinary arrangement, and it is believed that no more can be shown without sacrificing the advantages of the tabular arrangement.

The classification given herewith is based largely upon that of Rosenbusch, but it differs from the latter in various important respects, so that responsibility for it must lie with the author.

The first co-ordinate is in the direction normal to the paper, and

[1] *Handbook of Rocks*. 1906.

rocks belonging to a given series along this co-ordinate are placed within a single rectangle on successive sheets. For example, gabbro, essexite, and theralite form a series of this kind, the whole series to be observed simultaneously by looking through transparent paper for the second and third members. Along this co-ordinate igneous rocks are classified as normal or alkali-calcic (conveniently abbreviated to alkalcic), alkaline, and peralkaline.

Subsiliceous alkalcic rocks are characterized mineralogically by the absence of feldspars and feldspathoids and the presence of biotite, olivine, ferromagnesian (or mafic[1]), or calcareous-ferromagnesian (or calmafic), amphibole or pyroxene (or two or more of these). They are distinguished chemically by very low content of alkalies and alumina and high tenor of magnesia, lime, and iron. Mediosiliceous alkalcic rocks are characterized mineralogically by the presence of soda-lime feldspar nearly or wholly to the exclusion of alkali feldspar, and by the presence of biotite, olivine, mafic, or calmafic amphibole or pyroxene; they contain more soda than potassa (K_2O) and more than enough alumina to saturate the alkalies. Persiliceous alkalcic rocks are marked by the presence of soda-lime feldspar with dominant alkali feldspar, and with muscovite, biotite, or mafic or calmafic amphibole or pyroxene; chemically they are distinguished by the presence of both alkalies and lime with more than enough alumina to saturate the alkalies.

In general, alkalcic rocks are characterized by the presence of soda-lime feldspar (or no feldspar) with mica, olivine, mafic or calmafic amphibole or pyroxene, and the absence of feldspathoids (or lenads), soda-amphiboles, soda-pyroxenes, and lithia micas; they contain both alkalies and lime with more than enough alumina to saturate the alkalies.

Subsiliceous alkaline rocks are distinguished mineralogically by the absence of feldspars and lenads, and the presence of sodic and titaniferous amphiboles and pyroxenes; chemically they contain little alumina, and relatively large amounts of alkalies, titanic acid,

[1] The new terms felsic and mafic are here used in accordance with the proposal of Cross, Iddings, Pirsson, and Washington, *Jour. Geol.* XX (1912), p. 560, as short general terms, the first applying to feldspathic minerals and quartz, or rocks rich in such minerals, the second applying to all ferromagnesian minerals or rocks rich in such minerals.

and (often) ferric iron. Mediosiliceous alkaline rocks contain calcic plagioclase and a little lenad or alkali feldspar, and micas or soda-amphiboles or soda-pyroxenes; or they contain acid soda-lime feldspar with equal alkali feldspar and with micas, pyroxenes, amphiboles; chemically they contain in the first case high alkalies, lime, and titanic acid and low magnesia and silica, and in the second case high alkalies with potassa equal or dominant over soda, and abundant lime and alumina. Persiliceous alkaline rocks are characterized by dominant alkali feldspars, no soda-lime feldspar nor lenad, and lithia-mica, soda-amphibole, soda-pyroxene; they are very rich in alkalies and rarely in ferric iron, and very poor in lime and magnesia, and contain insufficient alumina to saturate the alkalies.

In general, alkaline igneous rocks contain sodic mafic silicates and no feldspar, or they contain more alkali feldspar and less soda-lime feldspar than the corresponding alkalcic rocks; chemically they contain more alkalies and less lime than the latter.

Peralkaline rocks are characterized mineralogically by the presence of feldspathoids (or lenads); they commonly contain also soda-pyroxene or soda-amphibole, or both. Chemically they are distinguished by insufficient silica to combine with the abundant alkalies to form feldspars after saturation of other available bases as orthosilicates.

In addition to the alkalcic, the alkaline, and the peralkaline, other divisions might be recognized, for example, the superalkaline, in which feldspars are entirely replaced by lenads. But this division consists of rocks which are very rare, and therefore it may be conveniently regarded as merely an extreme variation of peralkaline rocks. In spite of their rarity many names have been proposed for superalkaline rocks. Thus, by loss of feldspar, nepheline syenite becomes urtite, nepheline porphyry becomes sussexite, phonolite becomes leucitophyre, theralite changes to fergusite, tephrite to nephelinite or leucitite, olivine theralite to missourite, basanite to nepheline basalt or leucite basalt, and the volcanic equivalent of teschenite to analcite basalt. Another division might consist of the subsiliceous or lamprophyric rocks; but, with rare exceptions, such as shonkinite, the lamprophyric rocks are related

closely to gabbro, peridotite, or basalt, or their alkaline equivalents, and may be regarded as variations of such types.

The second co-ordinate extends from left to right across the paper and relates to mode of occurrence and conditions of formation; here again three classes are established, namely, plutonic, hypabyssal, and volcanic. Plutonic rocks solidified at considerable depth and have been later uncovered and brought to view through erosion. They form batholiths, stocks, and laccoliths. Hypabyssal rocks crystallized at moderate depth in the form of dikes, sills, or intrusions of irregular shape called chonoliths;[1] they are often called dike rocks. Volcanic rocks were brought to the surface (or near it) by volcanic action and form surface flows or intrusions near the surface. They also form beds and irregular aggregates through the accumulation of fragmental materials thrown out of volcanoes.

Plutonic rocks have granitic texture, that is, the essential constituents are crystalline anhedra of irregular shape and similar sizes, or dissimilar sizes showing gradations without a break from the smallest to the largest. Hypabyssal rocks may be divided into three types: the felsic, the aschistic, and the mafic. The aschistic or undifferentiated hypabyssal rocks commonly have porphyritic texture with abundant large phenocrysts and coarse granitic or aplitic groundmass. The felsic and mafic hypabyssal rocks commonly have aplitic texture, that is, they consist chiefly of fine evenly granular euhedral constituents, wholly crystalline. Some of these rocks have pegmatitic texture; others have porphyritic texture. The volcanic rocks commonly have glassy, felsitic, trachytic, or porphyritic textures; certain types have ophitic texture, in which the plagioclase feldspars in lath-shaped crystals are partly or wholly inclosed by mafic minerals.

The third co-ordinate extends from top to bottom of the sheet and relates to mineral composition; on this basis igneous rocks are divided into three primary groups: first, those in which alkali feldspar is dominant or in which felsic minerals including lenads are dominant, second, those in which soda-lime feldspar is equal to or dominant over alkali feldspar, or mafic minerals are equal to or

[1] R. A. Daly, *Jour. Geol.*, XIII (1905), 498.

dominant over felsic minerals including lenads, and, third, those containing no essential feldspar nor feldspathoid. Subdivisions are based largely upon quartz and olivine, since these minerals serve to measure the relative amount of silica present—the presence of quartz or the absence of olivine indicating a higher relative silication than the reverse condition.

It may be desirable to state explicitly that there are igneous rocks which will not readily find a place in this classification just as there are rocks which do not fit each other classification. Such a condition must exist, since rocks exhibit all sorts of gradations from one type to another, and classifications, on the other hand, establish sharply separated categories. A few illustrations will serve to emphasize this fact.

Rocks are classified as plutonic, hypabyssal, and volcanic, depending chiefly upon the depth at which they consolidate. But it is clear that there is a complete gradation in depth from the surface to the greatest depths open to observation. Similarly there is a gradation in the rocks formed at various depths. Hypabyssal rocks are found in dikes (or sills) consolidated at moderate depths. The same dikes may contain plutonic rocks at greater depths and volcanic rocks near the surface. Only those dike rocks which differ in some recognizable way from the plutonic and volcanic rocks are included as hypabyssal rocks.

Again, rocks are classified as alkalcic and alkaline. But there are many gradations from one type to the other. Granodiorite is an intermediate group of considerable importance. Assuming a total feldspar tenor of 60 per cent, Lindgren[1] has defined tonalite (or quartz diorite), as containing less than 8 per cent of alkali feldspar, granodiorite as containing 8–20 per cent of alkali feldspar, quartz monzonite, as containing 20–40 per cent of alkali feldspar, and granite as containing more than 40 per cent. The percentage of alkali feldspar cannot be accurately determined from an analysis of the rock because potassa (K_2O) may enter the plagioclase and soda may enter the orthoclase; it should be obtained by direct microscopic measurements. Granodiorite is intermediate between tonalite and quartz monzonite, and is therefore one of many con-

[1] W. Lindgren, *Amer. Jour. Science*, IX (1900), 269.

necting links between alkalcic and alkaline rocks. It is especially important because it constitutes large intrusions in California and elsewhere.

The volcanic equivalent of granodiorite, which may be appropriately called rhyodacite, forms another intermediate group between the alkalcic and the alkaline rocks. Having no distinctive name available, rhyodacites have been classed with dacites in the past; the two groups differ as distinctly as tonalite and granodiorite. It is because the rhyodacites and even some quartz latites have been described as dacites in the past that Daly[1] finds the average composition of dacite corresponding to that of granodiorite rather than tonalite. As may be seen from the tables of average composition of igneous rocks on pp. 217–221, dacite, like all the volcanic rocks, is more siliceous than the corresponding plutonic rock, tonalite, but is nevertheless its equivalent, as indicated especially by the tenor of alkalies. Similarly rhyodacite and granodiorite are related.

A rock which contains more ferromagnesian minerals (and less silica) than granite, but is nevertheless characterized by dominant alkali feldspar and quartz with subordinate plagioclase, has been called quartz syenite by Brogger.[2] It is sometimes regarded as intermediate between syenite and granite. But it is an alkaline and not an alkalcic rock type, and is very closely associated with quartz monzonite in the field. It should be regarded as a potassic variation from quartz monzonite, and not as a type closely related to granite. It is surprising to find that the average quartz syenite is less siliceous than the average quartz monzonite. This may be due to a tendency to classify the more siliceous quartz syenites as granites.

The relative depth at which rocks crystallized is estimated commonly by a study of their texture. Thus, plutonic rocks have granitic texture, volcanic rocks usually have felsitic or porphyritic texture; and textures are independent of mineral composition. But the ophitic texture, characterized[3] by the crystallization of

[1] R. A. Daly, *Proc. Amer. Acad.*, XLV (1910), 239.

[2] W. C. Brogger, *Zt. Kryst.*, XVI (1890), 81.

[3] A. N. Winchell, *Bull. Geol. Soc. Amer.*, XX (1908), 661.

plagioclase feldspars in lath-shaped forms before the solidification of the ferromagnesian minerals, is unknown in siliceous and ultrabasic rocks, and it is found in rocks crystallizing at moderate depth as well as in volcanic rocks. Independent of all other considerations, rocks having the ophitic texture are called diabase; they may occur in dikes or sills crystallizing at moderate depths, or they may be found in surface flows. Diabase proper has the mineral composition of augite andesite (or auganite); olivine diabase has the composition of basalt containing monoclinic pyroxene; quartz diabase and hypersthene diabase are also known.

The nomenclature employed is for the most part entirely familiar to petrographers. No distinction based on geological age is recognized; therefore such terms as melaphyre and quartz porphyrite are excluded. In designating the aschistic hypabyssal rocks the term porphyry is used (even for plagioclastic types) in preference to porphyrite. For the alkalcic plutonic and volcanic rocks it is believed that compound names like quartz diorite and augite andesite are objectionable, and should be replaced by simpler designations. Therefore, Spurr's[1] proposal to use tonalite in place of quartz diorite is adopted; and it is proposed to abbreviate augite andesite to the simple and almost self-explanatory form auganite.[2] Auganite proper is a volcanic rock consisting essentially of calcic plagioclase and augite; other varieties include hornblende auganite, related to andesite, and hypersthene auganite, which contains plagioclase and orthorhombic pyroxene with or without augite. A true augite andesite is a volcanic rock consisting essentially of sodic plagioclase (andesine or oligoclase) and augite.

That auganite deserves a distinctive name and is not merely a variety of andesite, as suggested by the name augite andesite, is well shown by field relations such as those existing at National, Nevada, where the important rocks are rhyolite, andesite, and auganite. At this locality the auganite and andesite are of wholly different age and wholly different appearance. The auganite might be confused with basalt without close examination, since it

[1] J. E. Spurr, *Amer. Geol.*, XXV (1900), 210, 232; *U.S. Geol. Surv. 20th Ann. Rpt.*, VII (1900), 188, 190.

[2] A. N. Winchell, *Mg. and Sci. Press*, November 22, 1912.

is black and dense; but its separation from the andesite is accomplished at a glance when both rocks are fresh.

A substitute for the compound name olivine gabbro is desirable but is not here suggested.

The average composition of each type of igneous rock should be available for comparison with the composition of rocks at given localities. Daly[1] has prepared tables giving these averages for certain rock types; in the following tables these have been supplemented by averages computed by the author.

In the tables of average composition, numbers 1, 4–7, 10, 13, 16, 19, 21, 23, 25, 26, 31–34, 36, 38, 40, 49–52, 54–57 were calculated by Daly;[2] the others have been prepared from data published by Rosenbusch (*Elemente der Gesteinslehre*, 3d edition, Stuttgart, 1910), and by Clarke (*U.S.G.S. Bulletin 419*, 1910), with the following exceptions. No. 3 is based on data of Rosenbusch (*loc. cit.*), Clarke (*loc. cit.*), and Osann (*Chemische Petrographie*, II, 1905). No. 9 is from data of Rosenbusch (*loc. cit.*), Clarke (*loc. cit.*), Osann (*loc. cit.*), and Weidmann (*Wis. Surv. Bull. XVI*, 1907). No. 14 is based on data of Rosenbusch (*loc. cit.*), Washington (*Jour. Geol.*, VII [1899], 57), and Ogilvie (*Jour. Geol.*, XVI [1908], 285). No. 15 is based on data of Rosenbusch (*loc. cit.*) and Osann (*loc. cit.*). No. 17 is from data of Rosenbusch (*loc. cit.*), Lacroix ("Minéralogie de Madagascar," *Nouv. Arch. Muséum*, I [1903], 30, 194), and Young (*Geol. Surv. Canada*, XVI, H, 1906). No. 27 is from data of Rosenbusch (*loc. cit.*) and Hore (*Econ. Geol.*, VI [1911], 54). No. 29 is from data of Rosenbusch (*loc. cit.*) and Doelter (*Akad. Wiss. Wien*, CXI, I [1902], 980). No. 37 includes 12 quartz keratophyres (Daly), 13 pantellerites (data of Rosenbusch), and 6 comendites (data of Rosenbusch). No. 44 is from data of Daly (*loc. cit.*), Clarke (*loc. cit.*), Rosenbusch (*loc. cit.*), and Osann (*loc. cit.*), auganites excluded. No. 47 is from data of Clarke (*loc. cit.*), Rosenbusch (*loc. cit.*), and Osann (*loc. cit.*), rocks containing acid plagioclase or orthoclase being excluded.

[1] R. A. Daly, *Proc. Amer. Acad.*, XLV (1910), 211.

[2] *Loc. cit.*

AVERAGE COMPOSITION OF PLUTONIC ROCKS

	1 Granite	2 Alkali-granite	3 Syenite	4 Alkali-syenite	5 Nepheline Syenite	6 Tonalite	7 Granodiorite	8 Quartz Monzonite	9 Quartz Syenite	10 Diorite	11 Monzonite	12 Nepheline Monzonite
No. of analyses.....	236	10	13	23	43	20	12	25	18	70	10	1
SiO_2..............	69.92	72.70	58.06	61.99	54.63	59.47	55.10	65.78	62.34	56.77	55.3[illegible]	46.40
Al_2O_3.............	14.78	12.12	16.25	17.93	19.89	16.52	15.82	15.71	15.06	16.67	15.91	21.60
Fe_2O_3.............	1.62	2.28	4.18	2.22	3.37	2.63	1.64	1.83	2.32	3.16	3.25	4.07
FeO..............	1.67	1.44	3.48	2.29	2.20	4.11	2.66	2.22	3.02	4.40	4.02	4.95
MgO..............	.97	.32	2.52	.96	.87	3.75	2.17	1.57	2.76	4.17	4.33	2.75
CaO..............	2.15*	.49	4.06†	2.55	2.51	6.24	4.66	3.76	3.98‡	6.74	6.86	8.44
Na_2O.............	3.28	5.42	3.67	5.54	8.26	2.98	3.82	3.35	3.56	3.39	3.73	6.29
K_2O..............	4.07	4.20	5.16	4.98	5.46	1.93	2.29	3.80	4.68	2.12	4.18	2.71
H_2O..............	.78	.82	1.37	.76	1.35	1.39	1.09	1.17	1.09	1.36	.67	1.25
TiO_2..............	.39	.09	.63	.56	.86	.64	.54	.53	.74	.84	.73	1.57
P_2O_5..............	.24	.12	.39	.14	.25	.26	.16	.18	.21	.25	.46	.26
MnO..............	.13	......	.23	.08	.35	.08	.05	.10	.24	.13	.11	......
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.29

* Includes 0.02 SrO and 0.06 BaO.

† Includes 0.11 SrO and 0.15 BaO.

‡ Includes 0.10 SrO and 0.34 BaO.

AVERAGE COMPOSITION OF PLUTONIC ROCKS—*Continued*

	13 Gabbro	14 Essexite	15 Theralite	16 Olivine Gabbro	17 Olivine Essexite	18 Olivine Theralite	19 Pyroxenite	20 Alkali-pyroxenite	21 Peridotite	22 Alkali-peridotite	
No. of analyses	24	6	4	17	6	2	4	3	49	1	
SiO_2	49.50	49.92	48.95	46.49	46.44	41.45	49.82	44.30	44.39	28.15	......
Al_2O_3	18.00	18.59	15.45	17.73	19.27	14.94	5.12	8.93	5.14	2.30	......
Fe_2O_3	2.80	4.19	3.97	3.66	3.85	7.76	1.83	7.94	3.88	21.61	......
FeO	5.80	5.01	4.63	6.17	6.02	7.72	7.44	7.75	6.70	15.93	......
MgO	6.62	2.66	5.24	8.86	4.33	6.11	19.55	10.29	29.17	20.67	......
CaO	10.64	7.32	10.70	11.48	8.65	10.44	13.00	15.28	6.13	3.45	......
Na_2O	2.82	5.67	4.30	2.16	4.90	5.69	.37	.74	.64	.63	......
K_2O	.98	3.05	2.29	.78	2.34	2.42	.21	1.05	.76	.29	......
H_2O	1.60	.91	2.21	1.04	1.18	1.51	1.06	1.18	1.80	3.45	......
TiO_2	.84	1.76	1.52	1.17	2.10	1.61	1.46	2.31	.88	2.55	......
P_2O_5	.28	.80	.47	.29	.81	.35	.05	Tr.	.14	Tr.	......
MnO	.12	.22	.17	.17	.11	......	.09	.23	.19	.45	......
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98	100.00	......

AVERAGE COMPOSITION OF HYPABYSSAL ROCKS

	Felsic Types								Mafic Types				
	23 Aplite	24 Alkali-aplite	25 Bostonite	26 Tinguaite	27 Plagi-aplite	28 Malchite	29 Alloche-tite	30 Beer-bachite	31 Minette	32 Kersan-tite	33 Camp-tonite	34 Fourchite (and Monchiquite)	35 Gare-waite
No. of analyses	15	6	5	15	10	6	2	1	10	20	15	16	1
SiO_2	75.00	74.40	61.32	55.02	68.75	60.18	50.19	47.21	49.45	50.79	40.70	45.17	42.84
Al_2O_3	13.14	13.11	18.43	20.42	16.36	17.81	22.40	20.52	14.41	15.26	16.02	14.78	4.60
Fe_2O_3	.58	.96	3.84	3.06	.78	1.38	3.03	7.48	3.39	3.29	5.43	5.10	5.69
FeO	.40	1.10	1.60	1.82	1.57	4.21	3.60	5.32	5.01	5.54	7.84	5.05	8.48
MgO	.30	.07	.46	.59	.63	2.92	1.95	4.16	8.26	6.33	5.43	6.26	24.60
CaO	1.13	.30	1.45	1.67	2.60	5.37	5.26	8.63	6.73	5.73	9.36	11.06	11.41
Na_2O	3.54	4.55	5.75	8.63	7.24	4.14	6.85	5.17	2.54	3.12	3.23	3.69	.61
K_2O	4.80	5.12	4.94	5.38	.68	2.56	3.40	.33	4.69	2.79	1.76	2.73	.42
H_2O	.71	.21	1.31	2.77	1.06	.65	2.46	.34	3.04*	5.71†	5.59‡	3.40	1.80
TiO_2	.30	.18	.89	.36	.28	.42	.86	.....	1.23	1.02	3.86	1.90	.....
P_2O_5	.05	Tr.	.....	.06	.05	.17	.....	.46	1.12	.35	.62	.51	.....
MnO	.07	Tr.	.01	.22	Tr.	.19	.....	.....	.13	.05	.16	.35	Tr.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.91	100.00	100.00	100.00	100.00	100.45

* Includes 0.61 CO_2. † Includes 2.61 CO_2. ‡ Includes 2.97 CO_2.

AVERAGE COMPOSITION OF VOLCANIC ROCKS

	36 Rhyolite	37 Alkali-rhyolite	38 Trachyte	39 Alkali-trachyte	40 Phonolite	41 Dacite	42 Rhyodacite	43 Quartz Latite	44 Andesite	45 Latite	46 Latite-Phonolite
No. of analyses	64	31	48	17	25	16	16	6	57	18	6
SiO_2	72.60	72.72	60.68	62.46	57.45	65.86	67.67	65.81	61.30	57.93	56.82
Al_2O_3	13.88	11.68	17.74	17.13	20.60	15.64	15.62	16.72	16.88	17.05	19.09
Fe_2O_3	1.43	3.09	2.64	2.89	2.35	2.56	2.00	3.10	3.01	3.88	2.81
FeO	.82	1.43	2.62	1.92	1.03	1.70	1.25	.55	2.76	2.66	2.06
MgO	.38	.35	1.12	.53	.30	1.71	.76	.66	2.49	2.13	1.19
CaO	1.32	.80	3.09	1.43	1.50	4.24	2.56	2.88	5.07	5.16*	4.10
Na_2O	3.54	5.66	4.43	6.30	8.84	3.93	4.10	3.73	3.99	4.19	6.67
K_2O	4.03	3.10	5.74	5.36	5.23	1.90	3.73	4.28	1.89	4.13	4.79
H_2O	1.52	.62	1.26	.97	2.04	1.77	1.61	1.52	1.33	1.52	1.18
TiO_2	.30	.23	.38	.61	.41	.47	.48	.43	.86	.87	.84
P_2O_5	.06	.08	.24	.15	.12	.14	.15	.17	.25	.40	.30
MnO	.12	.24	.06	.25	.13	.08	.07	.15	.17	.08	.15
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Includes 0.15 BaO.

AVERAGE COMPOSITION OF VOLCANIC ROCKS—*Continued*

	47 Auganite	48 Trachy-dolerite	49 Tephrite	50 Diabase	51 Olivine Diabase	52 Basalt	53 Olivine Trachy-dolerite	54 Basanite	55 Augitite	56 Picrite	57 Limburgite
No. of analyses..	73	10	24	20	17	161	27	16	6	3	7
SiO_2	54.97	50.93	49.14	50.12	50.10	48.78	48.74	44.20	42.25	43.24	41.69
Al_2O_3	16.69	19.06	16.57	15.68	14.43	15.85	16.41	15.64	16.26	15.19	14.80
Fe_2O_3	3.94	4.49	3.65	4.55	5.06	5.37	4.62	4.35	8.43	8.62	15.04
FeO	4.75	3.88	6.68	6.73	6.31	6.34	6.26	6.14	5.46	7.89	
MgO	4.13	2.72	3.98	5.85	7.32	6.03	4.29	8.89	5.49	8.56	8.64
CaO	8.02	7.04	9.88	8.80	9.53	8.91	8.06	9.74	9.75	13.78	11.98
Na_2O	3.19	4.91	2.57	2.95	2.75	3.18	4.08	4.03	4.45	.54	3.52
K_2O	1.45	3.47	3.39	1.38	.73	1.68	2.83	1.83	1.92	.48	1.17
H_2O	1.39	1.80	2.00	1.93	2.00	1.76	1.77	2.67	2.43	1.21	2.36
Ti_2O_2	.89	.74	1.00	1.41	1.25	1.39	1.85	1.64	2.52	.....	.67
P_2O_5	.28	.65	.84	.37	.27	.47	.80	.68	1.04	.49	.13
MnO	.30	.31	.30	.23	.25	.29	.29	.19	.....	.....	.....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

It should be remembered that rock names are not always used with the same meaning; therefore some of the averages presented herewith include analyses of rocks not classified in accordance with recent practice; this is especially true of the average for granite, which certainly includes some analyses of rocks which would now be classified as quartz monzonite, and probably includes also a few alkaligranites. The average for basalt probably includes analyses of trachydolerites. It is to be hoped that averages for these rocks will be prepared from analyses of rocks whose correct classification cannot be questioned.

If the average quantitative mineral composition of the various igneous rocks were known, it would be as useful as the average chemical composition. Of course the "normative mineral composition" can be calculated directly from the average chemical composition for each rock type. But the "normative mineral composition" is much less important than the "modal" mineral composition; it is merely the result of a distribution of the oxides among a certain group of minerals somewhat arbitrarily selected. In a few cases the actual (modal) mineral composition can be calculated at least approximately from the chemical composition. As our knowledge of the composition of the mineral constituents of each rock type increases, the mineral composition can be calculated for an increasing number of rocks.

A few calculations of this kind have been made; they are much facilitated by the use of Mead's circular slide rule.[1] For the alkaligranite all the ferric iron is assigned to riebeckite; alkaligranites often have, in place of riebeckite, either arfvedsonite, acmite, barkevikite, lithia mica, or two or three of these minerals. All the magnesia of the quartz monzonite is assigned to biotite and hornblende (including augite) in the ratio (about 3 to 1) required to prevent surplus of either lime or alumina in forming feldspars. The biotite and hornblende are assumed to have the composition obtained by analysis of those minerals from quartz monzonite from California (analysis *d*, Table XIV, and *a*, Table XIII, *Quant. Class. Ign. Rocks*). In calculating the mineral composition of the monzonite sufficient magnesia is assigned to biotite and hornblende to prevent

[1] W. J. Mead, *Econ. Geol.*, VII (1912), 136.

either an excess or a deficiency of silica in forming pyroxene. The biotite and hornblende are assumed to have the composition obtained by analysis of such minerals from monzonite (analysis *c*, Table XIV, and *b*, Table XIII, *Quant. Class. Ign. Rocks*).

As a preliminary, it is necessary to calculate the mineral composition in terms of the theoretical feldspar molecules; these may be changed into the feldspars actually present as follows. The feldspar of alkaligranite is either anorthoclase or perthitic albite with microcline or orthoclase. The second condition needs no further calculation; the first condition is obtained by simply combining the calculated orthoclase and albite. Andesine is the commonest plagioclase of quartz monzonite and monzonite; assigning to it the formula Ab_3An_2 the calculation results as follows:

APPROXIMATE AVERAGE MINERAL COMPOSITION OF ALKALIGRANITE, QUARTZ MONZONITE, AND MONZONITE

	1 Alkaligranite	2 Quartz Monzonite	3 Monzonite
Quartz	24.7	23.7	....
Orthoclase	24.7	....	....
Albite	38.7	....	....
Soda-orthoclase	....	24.4	33.9
Andesine Ab_3 An_2	....	36.2	34.0
Riebeckite	8.5	....	....
Ferriferous diopside	2.1	....	....
Pyroxene	....	3.1	18.8
Hornblende	....		3.2
Biotite	....	9.1	2.5
Magnetite	....	1.8	4.3
Ilmenite	0.2	....	....
Titanite	....	0.6	1.4
Apatite	0.3	0.4	1.1
(Water)	0.8	0.7	0.8
	100.00	100.00	100.00